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Dynamical short range pion correlation in ultra-relativistic heavy-ion interaction

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Abstract : The paper presents new data on two- and three-particle pseudo-rapidity correlation among showers produced in O^{16}–AgBr and ^{32}S–AgBr interactions at 60A GeV and 200A GeV respectively. The data have been compared with Monte-Carlo simulated values to look for true dynamical correlation in each case

Keywords : High energy physics, heavy-ion interaction, pion correlation

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1. Introduction

Studies in nuclear matter under extremes of energy and density are gaining momentum because of the possibility of observing some exotic phenomena. The study of correlation among the particles produced provides significant features of the nuclear interactions and is a potential source of information. The correlations can give direct information about the late stage of the reaction when nuclear matter is highly excited and diffused [1]. Several studies using well-known two-particle and three-particle correlation functions have been reported in hadron-hadron [2] and hadron-nucleus [3] collisions. The particles produced in different types of interactions (like hadron-hadron, hadron-nucleus) at high energies seem to be emitted preferably in a correlated fashion. But it is not possible to say with certainty why they prefer to do so. While some think that the larger part of the observed correlation effects, is conditioned by the production of the well-known resonances, hot multi-nucleon fireballs or formation of the exotic state of nuclear matter, the quark-gluon plasma, others observe the experimental data to favour formation of heavier intermediate states, clusterisation, *etc*. Moreover, the much-debated intermittency effect is also believed to be a manifestation of short-range correlations [Bose-Einstein correlations, the Hanbury-Brown Twiss (HBT) effect or the Goldhaber (GGL) effect for identical particles] [4]. In this context therefore, interest in the study of correlation is increasing rapidly. For a better understanding of correlation effect, it is necessary to investigate data of different projectiles covering the whole available energy spectrum. However, such studies in nucleus-nucleus interactions at high energies using different projectiles are rare. We present here some new data of ^{32}S–AgBr interaction at 200A GeV and ^{16}O–AgBr interaction at 60A GeV using some standard techniques to seek for true correlation of non-statistical origin. The experimental data of two- and three-particle correlation have been compared with the Monte-Carlo simulated values for the purpose.

2. Experimentation

Stacks of G5 nuclear emulsion plates horizontally exposed to a ^{32}S beam, having an average beam energy of 200 GeV per nucleon and an ^{16}O beam, having an average beam energy of 60 GeV per nucleon at CERN SPS have been used in this work. Leitz metalloplan microscopes provided with semi-automatic scanning stage are used to scan the plates, the scanning being performed by using oil immersion objectives of magnification $10x$ and $25x$ ocular lenses. The scanning is done by independent observers to increase the scanning efficiency which turns out to be 98%. The following criteria are adopted to select the events :

(a) The beam track must not exceed an angle of 3° to the mean beam direction in the pellicle.

(b) All the events having interactions within 20 μm from the top or bottom surface of the pellicle are rejected.

(c) The incident beam tracks are followed in the backward direction to ensure that events selected do not include interactions from the secondary tracks of other interactions; the latter events are removed from the sample.

The present analysis is based on the selected 150 primary events of ^{32}S–AgBr interactions and 250 primary events of ^{16}O–AgBr interactions. All the tracks of the charged secondaries in these events are classified according to standard emulsion terminology in the following way :

(i) The target fragments with ionisation > $1.4I_0$ (I_0 is the plateau ionisation) produce either black or grey tracks. The black tracks with range < 3 mm represent target evaporation particles of $\beta < 0.3$, singly or multiply charged particles.

(ii) The grey tracks with a range ≥ 3 mm and having velocity $0.7 \geq \beta \geq 0.3$ are mainly images of fast target protons of the energy range up to 400 MeV.

(iii) The relativistic shower tracks with ionisation < $1.4I_0$ are mainly produced by pions and are not generally confined within the emulsion pellicle. These particles are believed to carry important information about the nuclear reaction dynamics.

(iv) The projectile fragments formed a different class of tracks with constant ionisation, very long range and small emission angle.

To ensure the target in the emulsion to be Ag/Br, only those events are chosen in which number of heavily ionizing tracks are greater than eight. The heavily ionizing particles constituted of types (i) and (ii) belong to the target nucleus, those of type (iv) belong to the projectile nucleus, and the particles of type (iii) are those produced in the final state of the interaction. To distinguish between the singly charged produced particles and a projectile fragment of the same charge, we excluded all the particles falling into the cone of semi-vertical angle θ_c [5] ($\theta_c = 0.2/p_{\text{beam}}$, p_{beam} (GeV/c) is the incident beam momentum per nucleon) with respect to the projectile direction, from the present analysis.

The spatial angle of emission (θ) in the laboratory frame, of all the product particles, is measured by taking the space coordinates (x,y,z) of a point on the track, another point on the incident beam, and of the production point. For measurement, we have used oil immersion objectives of magnification 100x and 25x ocular lenses.

3. Method of analysis

3.1. Two-particle correlation :

Generally, the two-particle correlation function is defined as

$$C_2(y_1,y_2,p_{t1},p_{t2},s,A) = \sigma_{\text{in}}^{-1}(d^6\sigma/dy_1dy_2d^2p_{t1}d^2p_{t2}) - (\sigma_{\text{in}}^{-1})^2 \times (d^3\sigma/dy_1d^2p_{t1})(d^3\sigma/dy_2d^2p_{t2}), \quad (1)$$

where y and p_t denote the rapidity and transverse momentum of the particles respectively, A is the target mass number and s is the square of the centre-of-mass energy, the subscripts 1 and 2 denote the particles in the pair considered.

Integrating eq. (1) over p_t,

$$C_2(y_1,y_2,s,A) = \sigma_{\text{in}}^{-1}(d^2\sigma/dy_1dy_2) - (\sigma_{\text{in}}^{-1})^2(d\sigma/dy_1)(d\sigma/dy_2), \ldots \quad (2)$$

where

$$\sigma_{\text{in}}^{-1}\int(d^2\sigma/dy_1dy_2)dy_1dy_2 = \langle n_s(n_s-1)\rangle,$$

$$\sigma_{\text{in}}^{-1}\int(d\sigma/dy)dy = \langle n_s\rangle,$$

$$\int C_2 dy_1dy_2 = f_2,$$

f_2 being the multiplicity moment defined as

$$f_2 = \langle n_s(n_s-1)\rangle - \langle n_s\rangle^2.$$

Now, the two-particle correlation function can be written as

$$C_2(y_1,y_2) = \rho_2(y_1,y_2) - \rho_1(y_1)\rho_1(y_2), \quad (3)$$

where $\rho_2(y_1,y_2) = \sigma_{\text{in}}^{-1}d^2\sigma/dy_1dy_2$ and $\rho_1(y) = \sigma_{\text{in}}^{-1}d\sigma/dy$ are respectively the two- and one-particle densities, σ_{in} is the total inelastic cross section and $d^2\sigma/dy_1dy_2$ and $d\sigma/dy$

are the two and one-particle semi-inclusive distributions respectively. The normalized two-particle correlation function can be written as

$$R_2(y_1, y_2) = C_2(y_1, y_2)/\rho_1(y_1)\rho_1(y_2). \tag{4}$$

We choose pseudo-rapidity (η) as an approximated variable where $\eta = -\ln\tan(\theta/2)$, since the shower particles are primarily relativistic pions with $p_l^2 \gg p_t^2 \gg m_\pi$ for most of the pions. Thus, η is closely equal to the rapidity

$$y = 1/2 \ln [(E + P_l)/(E - p_l)].$$

Here p_l is the longitudinal momentum.

The two-particle correlation function [6] thus becomes,

$$\begin{aligned} C_2(\eta_1, \eta_2) &= \sigma_{\text{in}}^{-1}(d^2\sigma/d\eta_1 d\eta_2) - (\sigma_{\text{in}}^{-1})^2(d\sigma/d\eta_1)(d\sigma/d\eta_2) \\ &= N_2(\eta_1, \eta_2)/N - N_1(\eta_1)N_1(\eta_2)/N^2, \end{aligned} \tag{5}$$

where $N_1(\eta_1)$ is the number of showers with pseudo-rapidity between η and $\eta + d\eta$; $N_2(\eta_1, \eta_2)$ is the number of pairs of shower particles with pseudo-rapidity between η_1, $\eta_1 + d\eta_1$ and η_2, $\eta_2 + d\eta_2$. N is the total number of inelastic interactions in the sample. The normalised two-particle correlation function can be written as

$$\begin{aligned} R_2(\eta_1, \eta_2) &= \sigma_{\text{in}}(d^2\sigma/d\eta_1 d\eta_2)/(d\sigma/d\eta_1)(d\sigma/d\eta_2) - 1 \\ &= \text{N}[N_2(\eta_1, \eta_2)/N_1(\eta_1)N_2(\eta_2)] - 1. \end{aligned} \tag{6}$$

The correlation function $R_2(\eta_1, \eta_2)$ is related to the density of emitting sources [7].

3.2. Three-particle correlation :

The three-particle correlation function is also defined in a similar way :

$$\begin{aligned} C_3(z_1, z_2, z_3) &= \rho_3(z_1, z_2, z_3) + 2\rho_1(z_1)\rho_1(z_2)\rho_1(z_3) \\ &\quad - \rho_2(z_1, z_2)\rho_1(z_3) - \rho_2(z_2, z_3)\rho_1(z_1) - \rho_2(z_3, z_1)\rho_1(z_2), \end{aligned} \tag{7}$$

while the normalized three-particle correlation function is [8]

$$R_3(z_1, z_2, z_3) = C_3(z_1, z_2, z_3)/\rho_1(z_1)\rho_1(z_2)\rho_1(z_3), \tag{8}$$

where the quantities, $\rho_1 = 1/\sigma_{\text{in}}(d\sigma/dz)$, $\rho_2(z_1, z_2) = 1/\sigma_{\text{in}}(d^2\sigma/dz_1 dz_2)$,

$\rho_3(z_1, z_2, z_3) = (1/\sigma_{\text{in}})(d^3\sigma/dz_1 dz_2 dz_3)$ represent one-, two- and three-particle densities respectively. For relativistic shower particles, we may take η as a variable *i.e.*, $z = \eta$; thus equation (8) becomes

$$\begin{aligned} R_3(\eta_1, \eta_2, \eta_3) = {} & [\sigma_{\text{in}}^{-1}(d^3\sigma/d\eta_1 d\eta_2 d\eta_3) \\ & + 2(\sigma_{\text{in}}^{-1})^3(d\sigma/d\eta_1)(d\sigma/d\eta_2)(d\sigma/d\eta_3) \\ & - (\sigma_{\text{in}}^{-1})^2(d^2\sigma/d\eta_1 d\eta_2)(d\sigma/d\eta_3) \\ & - (\sigma_{\text{in}}^{-1})^2(d^2\sigma/d\eta_2 d\eta_3)(d\sigma/d\eta_1) - (\sigma_{\text{in}}^{-1})^2 \\ & (d^2\sigma/d\eta_3 d\eta_1)(d\sigma/d\eta_2)]/[(\sigma_{\text{in}}^{-1})^3\ (d\sigma/d\eta_1)(d\sigma/d\eta_2)(d\sigma/d\eta_3)] \end{aligned}$$

$$= N^2 N_3(\eta_1,\eta_2,\eta_3)/[N_1(\eta_1)N_1(\eta_2)N_1(\eta_3)]$$
$$- NN_2(\eta_1,\eta_2)/[N_1(\eta_1)N_1(\eta_2)]$$
$$- NN_2(\eta_2,\eta_3)/[N_1(\eta_2)N_1(\eta_3)]$$
$$- NN_2(\eta_3,\eta_1)/[N_1(\eta_3)N_1(\eta_1)] + 2, \tag{9}$$

where $N_3(\eta_1,\eta_2,\eta_3)$ is the number of triplets of shower particles at η_1,η_2 and η_3.

4. Monte-Carlo simulation

Correlation between the secondary particles produced in high-energy heavy-ion collisions can be studied by observing pseudo-rapidity (η) correlation among them. This may arise due to (i) the broad multiplicity distribution, (ii) the dependence of the one-particle spectrum, $d\sigma/d\eta$, on the multiplicity n, and (iii) the non-trivial correlations which occur due to kinematical constraints in the individuals events. To search for the correlation among the secondary particles in ^{32}S–AgBr interaction and ^{16}O–AgBr interaction, we have compared the experimental data with those obtained from the Monte-Carlo method. The simulation is made using the following assumptions :

(i) The shower particles are emitted statistically independently;

(ii) The multiplicity distribution in the ensemble of the Monte-Carlo events is the same as the empirical multiplicity spectrum of the real ensemble;

(iii) The one-particle spectrum $d\sigma/d\eta$, in the simulated interactions reproduces the empirical "semi-inclusive" distribution $d\sigma/d\eta$, with the corresponding n_s for the real ensemble.

This method has been successfully applied for hadron-nucleus and nucleus-nucleus interactions [9,10,11]. Gulamov *et al* [12] compared correlation function calculated from the inclusive ensembles of random events generated according to the method adopted here.

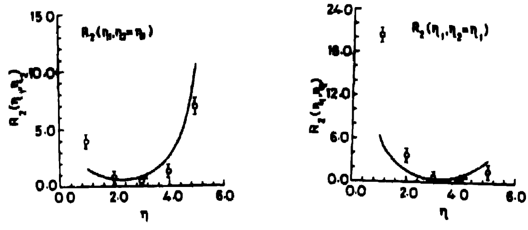
The observation of any excess short-range correlation over the Monte-Carlo values will indicate the presence of dynamical effects which cannot be explained by the conservation laws. For both two- and three-particle correlations we have compared the experimental values with the values obtained from Monte-Carlo calculations. The difference between experimental values R and Monte-Carlo values R_m can be interpreted as the dynamical surplus R_d which arises due to some kinematics in the reaction process. The dynamical surplus can be written as

$$R_d = R - R_m,$$

The surplus R_d can be interpreted as a manifestation of dynamical correlation.

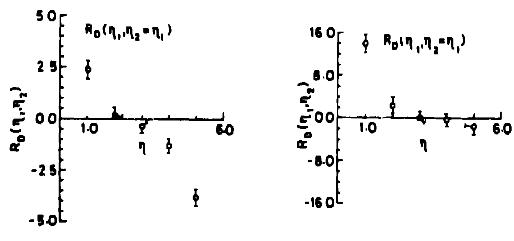
5. Results and discussion

The normalised two-particle correlation function $R_2(\eta_1, \eta_2 = \eta_1)$ *i.e.* the diagonal elements of the correlation matrix characterising the magnitude of short-range correlation at different pseudorapidity values for ^{16}O and ^{32}S events are shown in Figures 1(a) and 1(b) respectively. The solid lines in the figures represent values of correlation function due to Monte-Carlo calculations. Figures 2(a) and 2(b) give the dynamical surplus values in each case. The errors shown are only statistical [13] (the details are given in the appendix).



(a) (b)

Figure 1. The normalised two-particle correlation function for different values of η : (a) for ^{16}O events and (b) for ^{32}S events. The solid curves represent the Monte-Carlo simulated values



(a) (b)

Figure 2. The dynamical surplus correlation over the Monte-Carlo background . (a) for ^{16}O events and (b) for ^{32}S events.

Figures 3(a) and 3(b) represent the variation of normalised three-particle correlation function $R_3(\eta_1, \eta_2 = \eta_1, \eta_3 = \eta_1)$ *i.e.* the diagonal elements of three-particle correlation matrix also characterising the indication of short-range correlation of pseudorapidities for ^{16}O and ^{32}S events. The solid curves show the Monte-Carlo simulated values. The corresponding dynamical surplus for the three-particle correlation functions are shown in Figures 4(a) and 4(b) respectively.

One may draw the following inferences from the above analysis :

(1) The two-particle short-range dynamical correlation exists in the target fragmentation region $\eta = 1$ for both ^{16}O and ^{32}S events and in the projectile fragmentation region ($\eta = 4$ and 5) for ^{16}O events and $\eta = 5$ for ^{32}S events.

(2) The three particle dynamical correlations are prominent at $\eta = 1$ and 5 in case of ^{16}O events and $\eta = 1, 2$ and 5 in case of ^{32}S events.

Finally, one may conclude that both two- and three-particle dynamical correlations exist among pions produced in ^{16}O–AgBr and ^{32}S-AgBr interactions. It is also interesting to note that in case of ^{32}S–AgBr interaction (heavier projectile with increased energy), correlation occurs in additional phase space compared to ^{16}O–AgBr interaction (lighter

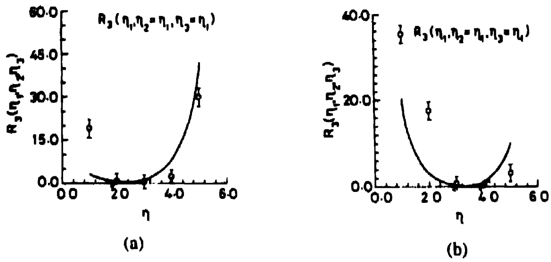


Figure 3. The normalised three-particle correlation function for different values of η : (a) for ^{16}O events and (b) for ^{32}S events. The solid curves represent the Monte-Carlo simulated values.

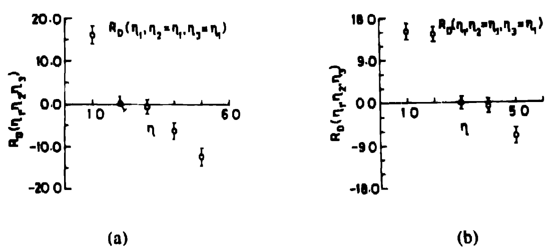


Figure 4. The dynamical surplus correlation over the Monte-Carlo background : (a) for ^{16}O events and (b) for ^{32}S events.

projectile at low energy). The data are helpful for an understanding of the physics involved in the particle production in ultra-relativistic heavy-ion interactions.

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Appendix

The calculation of errors :

Experimentally, the two-particle correlation function is calculated as

$$R(\eta_1,\eta_2) = <n_1 n_2>/[<n_1><n_2>] - 1, \qquad \text{for } \eta_1 \neq \eta_2$$

$$= <n(n-1)>/<n^2>-1, \qquad \text{for } \eta_1 = \eta_2,$$

where n_1 and n_2 are the shower multiplicities in a small interval of δ_n around η_1 and η_2. The variance in R is given by

$$\begin{aligned} V[R] = \Big\{ & \langle n_1\rangle^2\langle n_2\rangle^2\langle n_1n_2\rangle^2 - 2\langle n_1^2n_2\rangle\langle n_1n_2\rangle\langle n_1\rangle\langle n_2\rangle^2 \\ & - 2\langle n_1n_2^2\rangle\langle n_1\rangle^2\langle n_2\rangle\langle n_1n_2\rangle + \langle n_1^2\rangle\langle n_1n_2\rangle^2\langle n_2\rangle^2 \\ & + \langle n_2^2\rangle\langle n_1n_2\rangle^2\langle n_1\rangle^2 + 2\langle n_1n_2\rangle^3\langle n_1\rangle\langle n_2\rangle \\ & - \langle n_1n_2\rangle^2\langle n_1\rangle^2\langle n_2\rangle^2 \Big\}\Big[N\langle n_1\rangle^4\langle n_2\rangle^4\Big]^{-1} + O(1/N^2) \end{aligned}$$

for $\eta_1 \neq \eta_2$,

and

$$\begin{aligned} V[R] = & \langle n^4\rangle\langle n\rangle^2 - 4\langle n^3\rangle\langle n^2\rangle\langle n\rangle + 4\langle n^2\rangle^3 - \langle n^2\rangle^2\langle n\rangle^2 \\ & + 2\langle n^2\rangle\langle n\rangle^2 - 4\langle n^2\rangle^2\langle n\rangle + 2\langle n^2\rangle\langle n\rangle^3 \\ & + \langle n^2\rangle\langle n\rangle^2 - \langle n\rangle^4 \Big\}\Big[N\langle n\rangle^6\Big]^{-1} + O(1/N^2), \qquad \text{for } \eta_1 = \eta_2. \end{aligned}$$

N is the total number of inelastic events, $0(1/N^2)$ is a polynomial which is negligible when calculating the errors, in comparison with the other terms. Similarly, the three-particle correlation function is experimentally obtained as

$$R(\eta_1, \eta_2, \eta_3) = \langle n(n-1)(n-2)\rangle / \langle n\rangle^3 - 3\langle n(n-1)\rangle / \langle n\rangle^2 + 2, \qquad \text{for } \eta_1 = \eta_2 = \eta_3.$$

The variance of this quantity is calculated term by term and instead of giving the long algebraic expression of the net variance, we have computed it and shown the corresponding errors in the figures.